Pixel Array Germanium Detectors for Nuclear Physics (PAGe)

Grant Award Number: DE-SC0015137
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A collaboration with David Radford at Oak Ridge National Laboratory

- PHDS Co. Introduction
- Motivations for Pixel Array Approach
- Prototype Pixel Detector Geometry
- Waveform (Signal) Decomposition
- Path Forward
PHDS Co.

• Est. Fall 2004 – Nuclear and Solid State Physics Origin
  • History: Custom Nuclear-Physics Detectors
  • Recently: Modular HPGe Systems

• Complete Germanium Detector Manufacturing and R&D
  • Concept Design
  • Crystal Growth
  • Detector Fabrication
  • System Integration
  • Software application
  • Sales & Service

Make new HPGe detector capabilities available
Why Pixel Array Germanium?

- PHDS growing ever-larger germanium crystals
- Investigating best strategy for fabricating position-sensitive gamma-ray detectors with excellent spectral and spatial resolution
- Traditionally orthogonal-strip design, but there are limitations
Orthogonal Strip Limitations

- Best obtainable high-frequency (series) noise when the capacitance of detector segment is not greater than that of the JFET
- Strips are necessarily longer (higher input capacitance) as detector area grows
  - 90-mm GeGI strips: 5-mm wide = 45 pF
  - 140-mm 16-channel strips: 7.75-mm wide = 76 pF
- Can make strips more narrow, but this solution is not readily scalable

![Graphs showing energy resolution with different time constants](image-url)
Pixel Approach Advantages

• Design pixel geometry for minimal series noise
• Readily scalable: solution for 90-mm wafer the same as for 140+ mm wafer (at the expense of more data processing channels)
• Naturally gain count-rate capacity
• Apply well-tested waveform decomposition algorithms for optimal spatial resolution

For Example (from Phase-I proposal):
First Pixel Detector at PHDS

- Based on modeling and existing research cryostat limitations, use 37 hexagonal pixels that form a hexagonal envelope
- Hexagonal wafer – fast cuts with minimal material loss; tile with minimal dead space between modules
First Pixel Detector at PHDS

- Use existing research cryostat with 36 feedthroughs
- Standard detector fabrication recipe using stainless steel thin metal mask (hex pixels)
- Instrument 33 pixels, AC guard ring, DC guard ring, and AC contact
Pixel Waveform Decomposition

• Collaboration with David Radford at ORNL (leverage significant GRETINA development/experience)
• Uses a “signal basis” – a set of simulated signals
• Digital signal processing to determine the number, positions, and energies of gamma interactions in the crystal

![Diagram](image-url)
Step 1: Field Generator

- Adapt existing weighting potential calculator to the pixel geometry – FIELDGEN-HEX
- Calculate weighting potential on 0.125-mm grid (3D)
- Based on symmetry of array, calculations only needed for 6 pixels
- Use weighting potential and detector operating parameters to generate charge waveform in each pixel for any gamma-ray interaction location in the detector
Step 2: Signal Generator (Basis Set)

- Generate set of basis signals used to fit measured pixel signals (SIGGEN-HEX)
- Each basis signal comprised of 20 samples of 20 ns
- Basis set generated on 0.5-mm grid
  - Expected spatial resolution on the order of mm
  - 376k signals in basis set
Step 3: Signal Decomposition

- Phase I – single-site, coarse grid search
  - Select basis set element/position that best fits data
  - Simple $\chi^2$ minimization on the grid locations
- Analyze photopeak data at 122 keV – most of these interactions are single-site
- Focus on central pixel (19) and nearest neighbors (12, 13, 18, 20, 25, 26)
Energy Resolution

- Expect energy resolution to be better than that of commercial GeGI strip based on reduced capacitance (~850 eV vs. 1.2 keV at 122 keV with $T_p = 5 \, \mu s$)
- Energy resolution measured to be $0.90 - 1.35$ keV across the full detector (at 122 keV)
Spatial Resolution

- Commercial GeGI applies parametric interpolation of fast signal to calculate gamma-ray interaction location.
- Compare this approach with 1st order waveform decomposition (4 spot locations on Pixel 19; 0.5-mm collimator)

**Parametric Interpolation**

**Waveform Decomposition**

- $\text{FWHM}_{x,y} = (4.4 +/\ 0.2) \text{ mm}$
- $\text{FWHM}_z = (2.0 +/\ 0.1) \text{ mm}$

- $\text{FWHM}_x = (3.1 +/\ 0.2) \text{ mm}$
- $\text{FWHM}_y = (2.5 +/\ 0.2) \text{ mm}$
- $\text{FWHM}_z = (3.0 +/\ 0.5) \text{ mm}$
Phase II Prototype Detector

- Compact design to facilitate close packing of arrays for large germanium detectors
- New, smaller form factor preamplifier design (next slide)
New Preamplifier Design

- Reduced footprint of preamplifier such that it fits in the “shadow” of a pixel
- Surface area reduced from 394 mm$^2$ to 200 mm$^2$
- Fully tested/vetted and now used in commercial GeGI systems!
Phase II Signal Decomposition

• With the assistance of our collaborator, implement the full multi-site waveform decomposition algorithms employed in GRETINA

• Strengths:
  – Provides superior spatial resolution (relative to parametric interpolation)
  – Able to identify up to 2 interactions per segment (currently these are treated as single interactions)
  – Fast performance (even relative to simple Phase-I approach)

• Weaknesses:
  – Strongly relies on fidelity of the basis set
  – Poor determination of number of interactions
  – Significant effort required to adapt from GRETINA to Pixel Array (ongoing effort)
Single-Site Signal Decomposition

Phase-I (slow)
FWHM$_x$ = 3.28 mm
FWHM$_y$ = 2.47 mm

Phase-II (fast)
FWHM$_x$ = 2.16 mm
FWHM$_y$ = 2.28 mm

- Resolution based on Gaussian fit of row/column with max value
- Bin size is 0.5 mm in X and Y dimensions
- (Collimator is 0.5 mm diameter hole in 1/8” thick Pb)
Multi-Pixel Signal Decomposition

- Now looking at $^{137}$Cs data with interactions in multiple pixels
- Currently working on geometry module that will more efficiently keep algorithm from “wandering” out of pixel
- Example data and fits below...

![Waveform Data](image1)

Waveform Data
37 Pixels x 20 Time Steps

![Waveform Data](image2)

Waveform Data
37 Pixels x 20 Time Steps
Next Steps

• Finish assembling and load detector into prototype PAGe
  – All 37 pixels will be instrumented
  – For testing, two GeGI signal processing boards will be used (32-channel SPECT)

• Continue development of waveform decomposition for PAGe
  – Promising results thus far
  – Cross-talk appears to be minimal, but need to investigate this further

Questions?